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TURBULENT LIFT

Comments on some preliminary wind tunnel tests.

R.A. Westesson, U. Clareus et al.

Translation of "Virvellyft. Kommentarer till några preliminära vindtunnelprov." Saab-Scania Report, TP-74-51, March 1, 1974, 28 pp.

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16. Abstract

Three-dimensional tests were carried out to establish a stable and useful vortex in the tangential direction over a straight wing using tangential blowing on the upper side of the wing. When the tangential blowing was sufficiently strong, contact flow was obtained at very high angles of incidence. Quantitative data indicated that there was a decreased total drag at increasing tangential blowing and constant α.

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TURBULENT LIFT

Comments on some preliminary wind tunnel tests.

During 1973 three-dimensional tests with turbulent lift were carried out in the form of a thesis in applied aerodynamics. Ulf Clareus and Rolf A. Westesson prepared and made wind tunnel tests on a number of wing models (7). The work was sub-divided into a qualitative part with visualization of the flow in the smoke tunnel and a quantitative part with a straight wing, number 8, in a test tunnel. /1*

The purpose of the study was "to try to establish a stable and useful vortex in the tangential direction over a straight or almost straight wing".

The qualitative tests showed that a stable vortex can be generated by means of tangential blowing in a vortex slot on the upper side of the wing. If the tangential blowing is sufficiently strong, contact flow can be obtained even at very high angles of incidence ($\alpha_{max} \approx 80^{\circ}$).

Quantitative data are obtained from the test tunnel which indicate that there is a decreased total drag at increasing tangential blowing and constant α. At very high blow coefficients and lifting force output (e.g., $C_{\mu} = 0.8$, $C_L = 5$, $C_D = 1.6$ at $\alpha = 32^{\circ}$) one obtains an induced drag which is less than the formula $C_{Di} = C_L^2/\pi\Lambda$ indicates. This PM (unknown abbreviation) will try to describe and explain this phenomenon.

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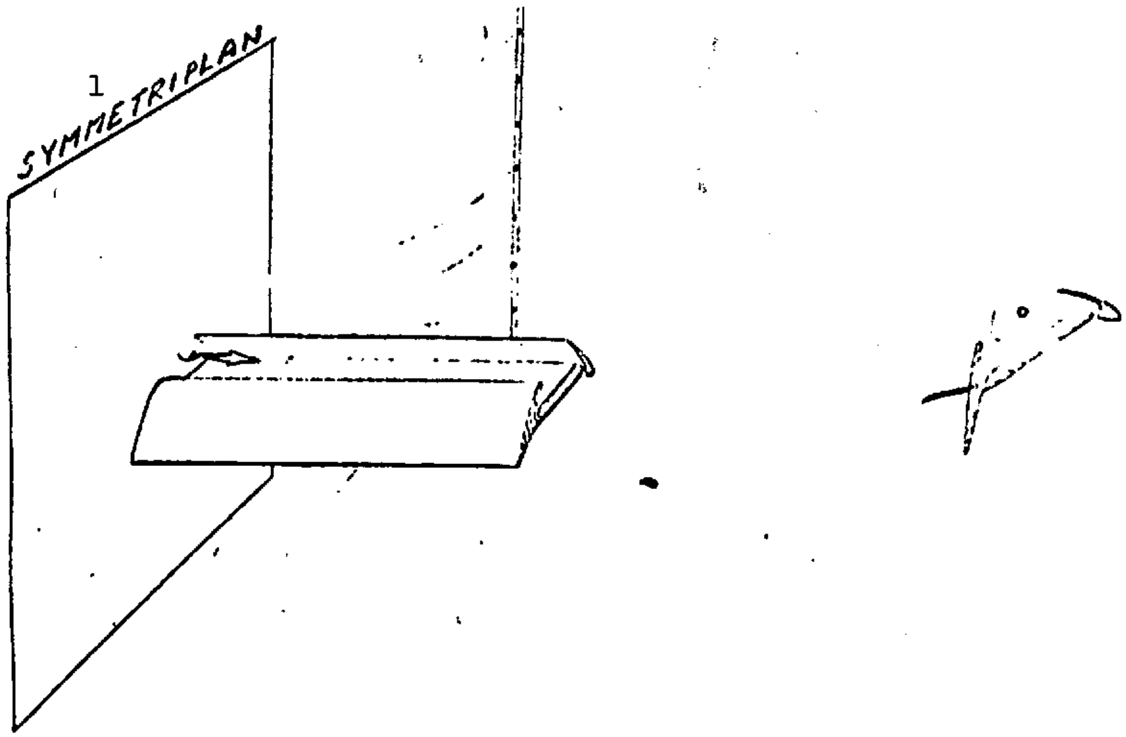
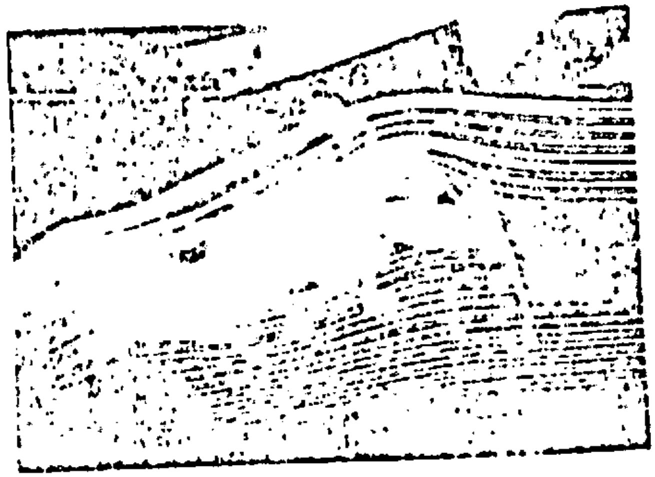
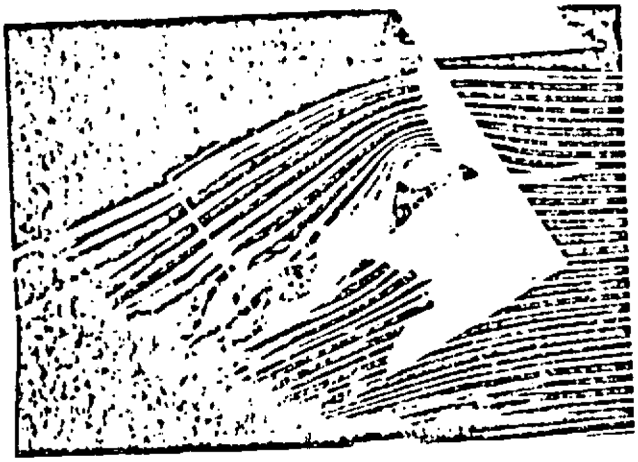
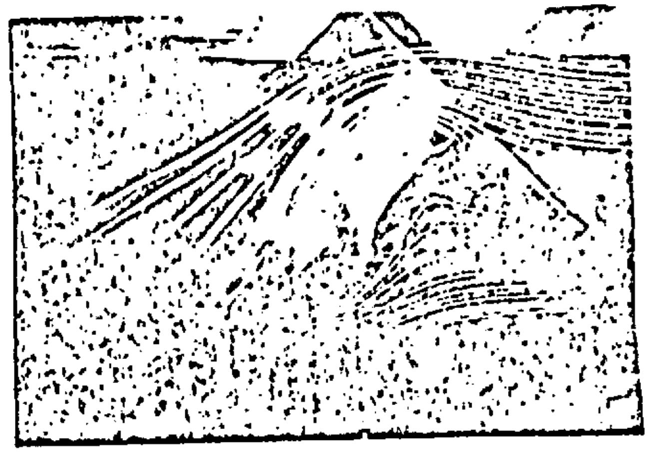
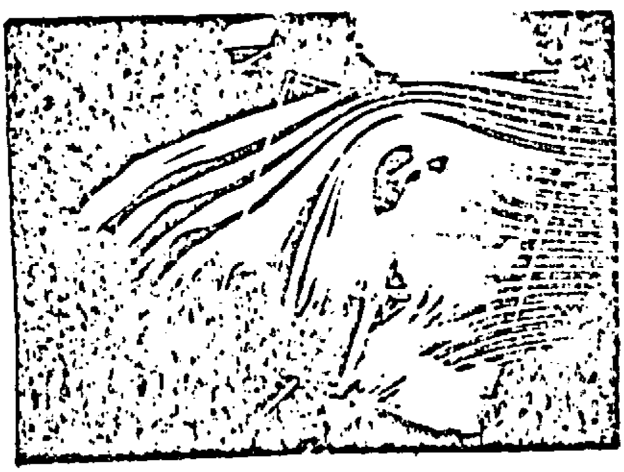
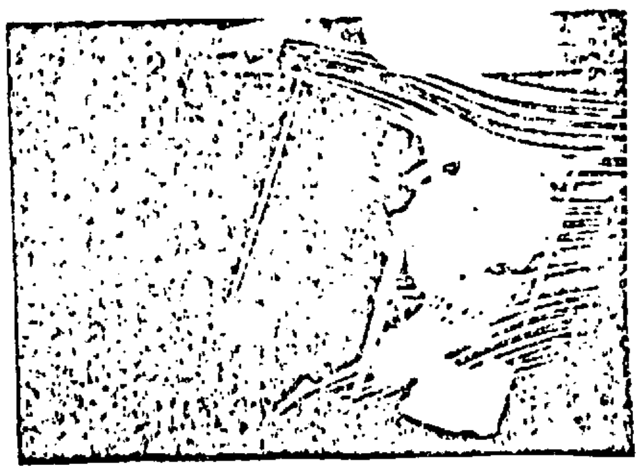
* Numbers in the margin indicate pagination in the foreign text.



Key: 1. Plane of symmetry.

/2

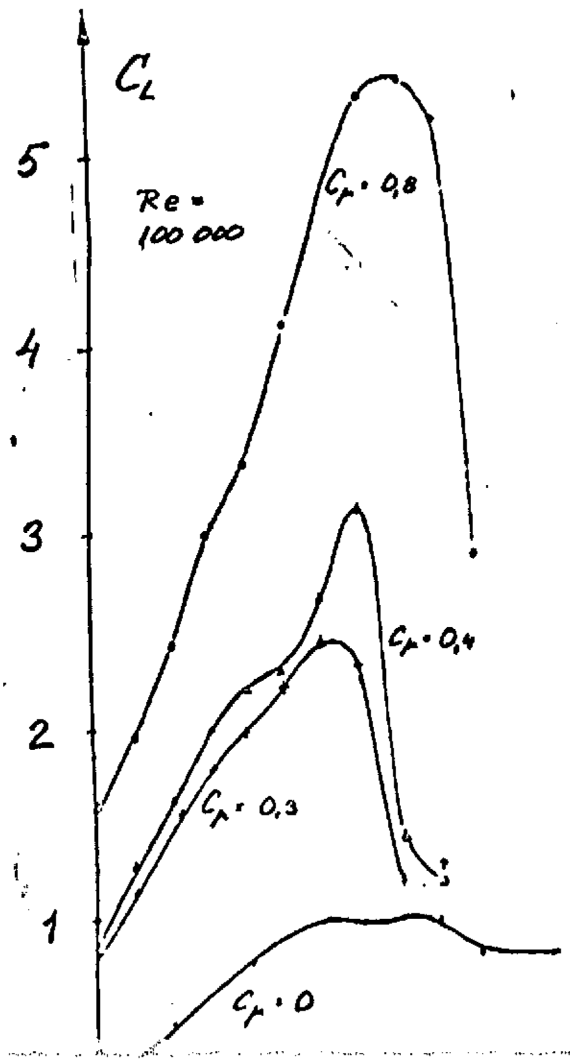







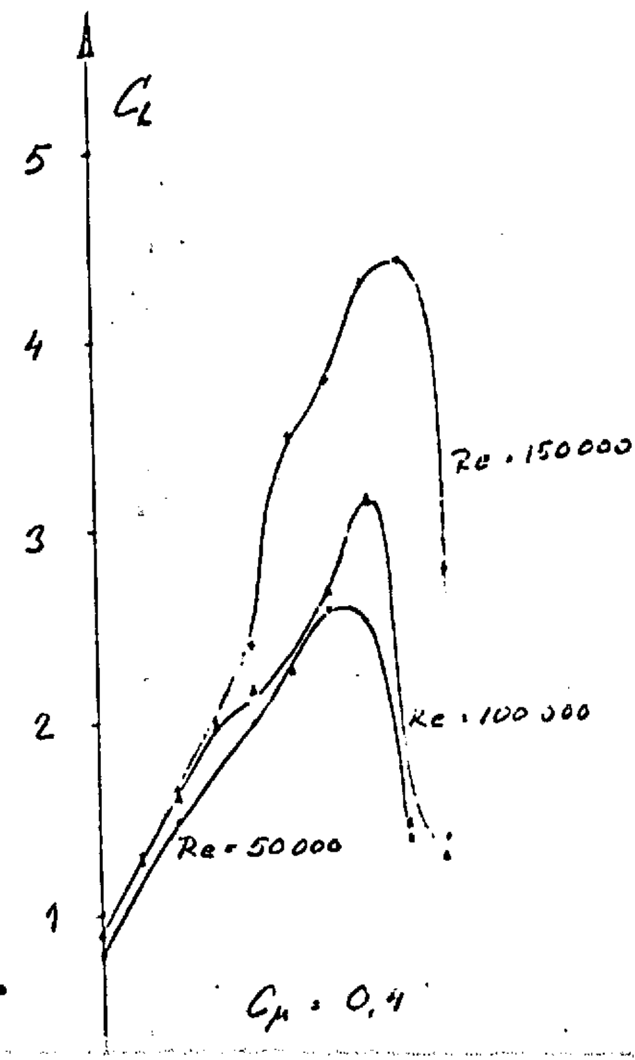
The Effect of α and Re

Two diagrams in this thesis (ref. 1) show the dependence of α and Re and are shown here. /3

Diagram 1 shows how the lift coefficient depends on the angle of incidence and the blow coefficient. The diagram indicates that the lift force increases stepwise when vortex flow is initiated. An additional increase in tangential blowing has very little effect on $C_L = f(\alpha)$ for small angles of incidence, but makes larger angles of incidence possible and results in higher C_{Lmax}.

Diagram 2 below shows how the Reynolds numbers vary. Data show that the vortex collapse comes later at higher Re numbers.





Lifting force and drag

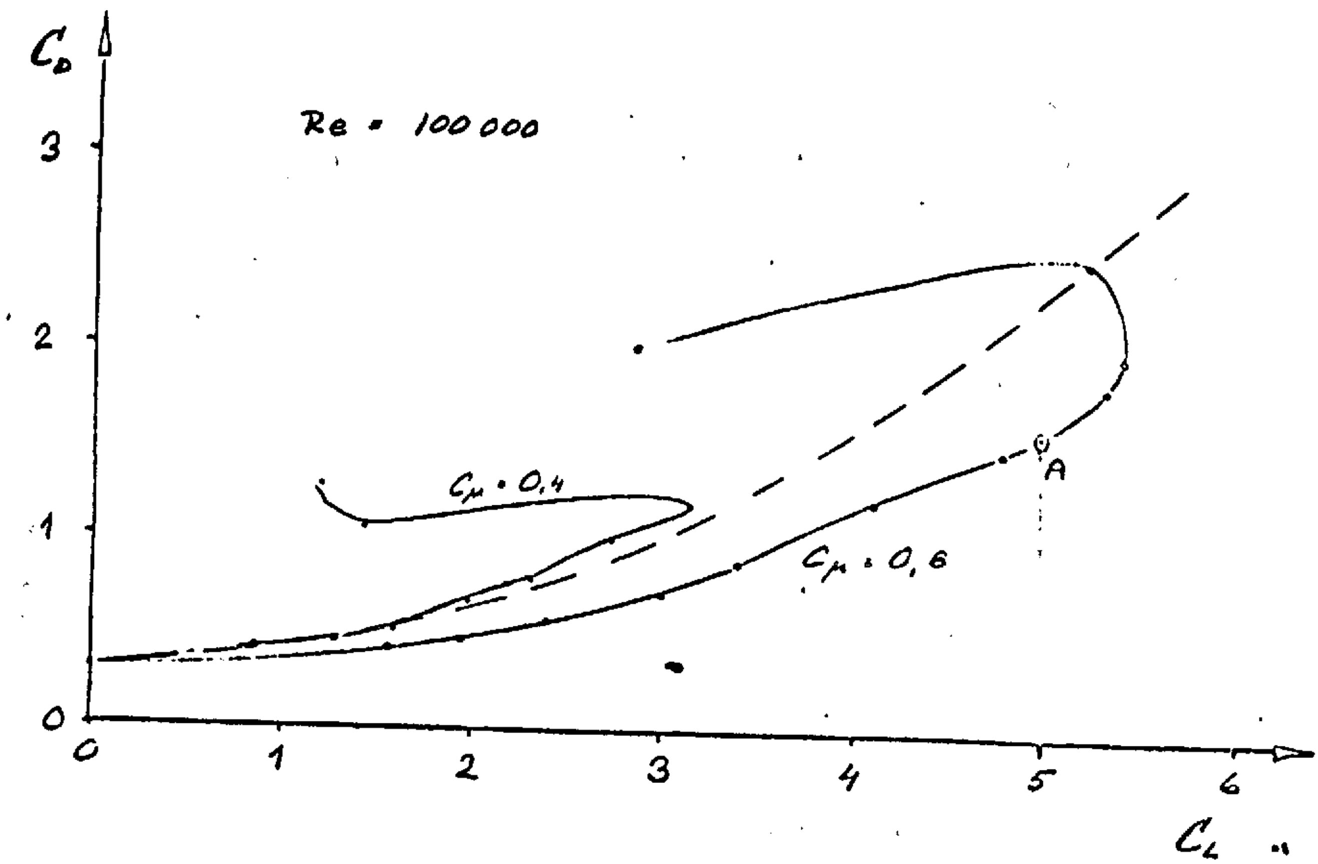
Diagram number 3 below is a compilation of data from two figures, 8.14 and 8.16, in the thesis. /4

By means of the measured points the zero point drag can be extrapolated to $C_{D0} = 0.28$. On the basis of the zero point drag a dotted curve has been drawn which follows the equation

$$C_D = 0.28 + \frac{1}{\pi \cdot \Lambda \cdot e} \cdot C_L^2$$

with the following values inserted: $\Lambda = 4$ and $e = 1$.

For very high blow coefficients and lifting force output, e.g., $C_\mu = 0.8$, $C_L = 5$, one obtains a drag $C_D = 1.6$ which is less than the $C_D = 2.27$ which can be calculated from the above formula!

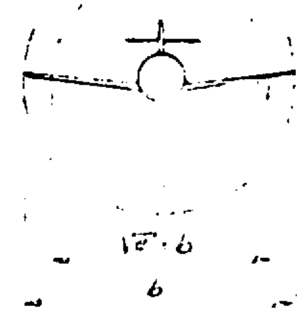


Lifting force and induced drag

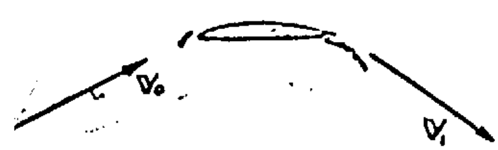
The formula for the drag of a wing with finite /5
span is normally written as follows:

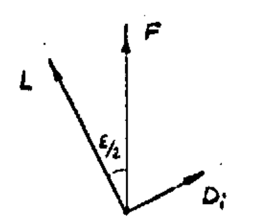
$$C_D = C_{D0} + \frac{1}{\pi \cdot \Lambda \cdot e} \cdot C_L^2 \qquad (1)$$

The formula can be derived from the picture of air flow in the form of a flow tube with a diameter equal to the span which deviates by a small angle ε to generate an impulse F (ref. 4).

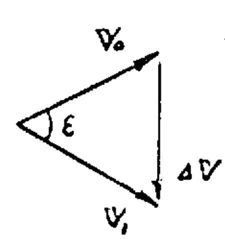


The formula contains the side ratio = $(\text{span})^2$ divided by the wing surface ($\Lambda = b^2/S$) and an ellipse factor e (efficiency factor) which indicates the fraction of the flow tube cross-section which in practice is deflected by the wing. For aircraft 105, for instance, $e \simeq 0.7$ in the low speed range. In the formula it is also assumed that the angle ε is so small that $\sin \varepsilon = \varepsilon$. At $\varepsilon = 30^\circ$ this results in an error of 6 %, and for downward deflection $\varepsilon = 60^\circ$ the error becomes 33 %, and for $\varepsilon = 90^\circ$ the error is 100 %.





An additional assumption is that the friction drag can be completely separated from the induced drag. In the formula it is assumed that all friction drag is included: the terms C_{D0} and the impulse drag part are based on the fact that the impulse only depends upon the deflection angle and do not include the speed reduction



in the deflected air flow.

If the trigonometric simplification for small angles ($\sin \varepsilon = \varepsilon$ and $\cos \varepsilon = 1$) is not included in the assumptions, the formulas for lifting force and drag can be derived again and will then have the following form:

$$C_L = 1/2 \cdot \pi \cdot \Lambda \cdot e \cdot \sin \varepsilon \qquad (2)$$

$$C_D = C_{D0} + \frac{1}{\pi \cdot \Lambda \cdot e \cdot (\cos \varepsilon/2)^2} \cdot C_L^2 \qquad (3)$$

A comparison between theory and test results /6

The pair of formulas (2) and (3) contains the variables C_L, C_D, C_{D0}, ε and e. With a known C_{D0} and a coordinated pair of values for C_L and C_D, the downward deflection angle ε and the ellipse factor e can be calculated.

$$\varepsilon = 2 \cdot \operatorname{arctg} \frac{C_D - C_{D0}}{C_L}$$, from which

$$e = \frac{2 \cdot C_L}{\pi \cdot \Lambda \cdot \sin \varepsilon}$$ can be calculated.

Wind tunnel data from the diagram on page 4 are selected as an example. Lifting force and drag values are selected for a configuration with strong tangential blowing: $C_\mu = 0.8$ and a large angle of attack $\alpha \approx 32^\circ$ for which $C_L = 5.0$ and $C_D = 1.60$. The zero lift drag $C_{D0} = 0.28$ (extrapolated). The wind tunnel model consisted of a half model, a right wing, with the chord = 100 mm and one half the span = 200 mm, i.e., $\Lambda = 4$.

By substituting these parameters we obtain:

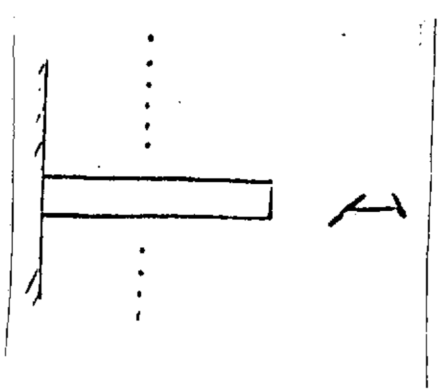
(A)
$$\varepsilon = 2 \cdot \mathrm{arctg}\,\frac{1.60 - 0.28}{5.0} = 29.6^{0}$$

$$e = \frac{2 \cdot 5.0}{\pi \cdot 4 \cdot \sin 29.6} = 1.61$$

Thus the pair of values for lifting force and drag correspond to the impulse from a downward deflection of approximately 30° and an air flow corresponding to a flow tube with a cross sectional area which is greater than a flow tube with the span as diameter! In practice data should indicate an artificial span increased by a factor $\approx \sqrt{e} = 1.27$. Is this possible?

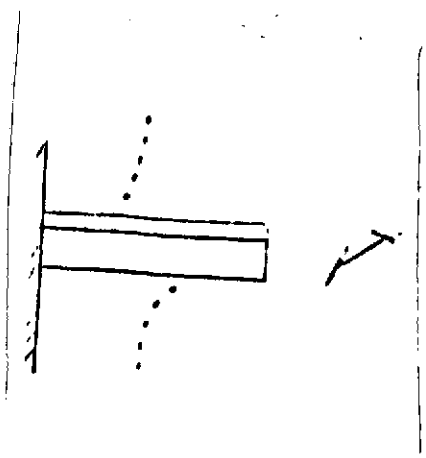
A couple of observations in the smoke tunnel /7

When model number 7 was run in the FFA smoke tunnel, the author made some subjective observations which may complement the results that are presented in the thesis.

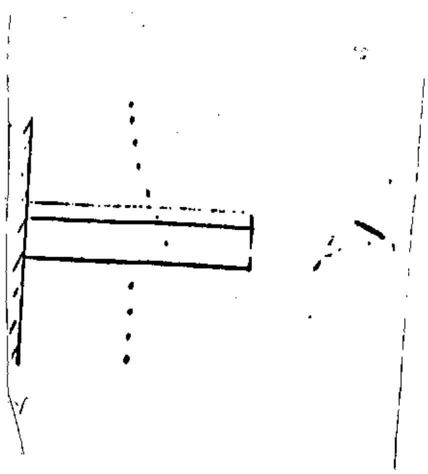


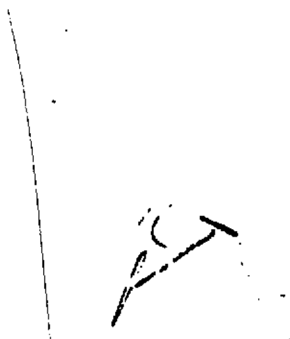
I placed myself behind the measurement distance approximately 1 meter behind the half models of the wing and let the kerosene smoke pass by my nostrils. Thus in front of me I had the wing model oriented with the wing tip to the right and the base of the wing with its end disk or the aircraft plane of symmetry to the left of the vertical flow plane which the stream of smoke formed. I adjusted the position of the head so that the symmetry plane of the head coincided with the streaks of smoke. The streaks of smoke passed the wing profile approximately half way between the base and the tip of the wing. The wing model was initially in a position corresponding to $\alpha = 0$ and without tangential blowing.

When the angle of incidence of the model was increased, the streaks of smoke were displaced so that the streaks of smoke on the upper side of the wing moved down and pulled in against the base of the wing while those on the lower side moved out towards the wing tip. A strong wake separated those streaks of smoke which passed close above and below the wing profile. The wake and the flow around the wing tip rolled up into a rotational movement behind the model.



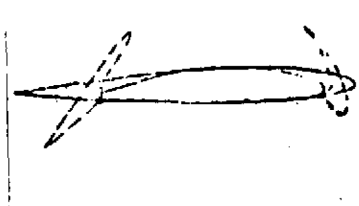
When the tangential blowing was started and increased in intensity, the displacement of the flow plane the smoke streaks formed was decreased. When the tangential blowing reached such a level that the smoke streaks above and below the wing profile were in approximately the same plane again, the flow was markedly stabilized. This stabilization took place suddenly. When later on the tangential blowing was increased further, a displacement of the smoke plane took place in the other direction. The streaks of smoke on the upper side were blown out towards the wing tip, more so than for the lower side. The streak of smoke which was closest to the upper side of the wing moved down in the vortex slot and was ejected tangentially.





When the same process was studied from the side, one could not see the displacement of the streaks of smoke as clearly, but on the other hand one could see how the wake behind the model was decreased with increasing tangential blowing. When the flow picture was suddenly stabilized, the stream of smoke closest to the upper side of the wing became approximately parallel to the upper side of the rear flap after it had bent around the nose flap and arched over the "vortex slot". When the tangential blowing was very strong, one or more streaks of smoke moved up from the flow tangentially in the vortex slot between the nose flap and the rear edge flap (see pictures page 2).

Judging from these observations it requires a certain minimum /8
transport of air tangentially in order to establish the qualitative air flow picture which has been designated as vortex lift. When the flow picture is well established, it seems that it may be possible to quantitatively increase the lifting force and/or decrease the induced drag through increased tangential blowing, according to data from the test tunnel.



A few more observations should be mentioned. Models 7 and 8 were built taking into consideration a large number of practical constructive aspects. Vortex lift is considered as a high lift mode only in connection with starting and landing. The problem then becomes to be able to "fold up" the vortex slot" inside a thin profile suitable for cruising speed (ref. 2). The flaps at the front and the rear edge of the wind tunnel model were for this purpose built with such a geometry that it should be possible to fold them up inside an approximately 10% thick wing profile.

During blowing in the smoke tunnel with high attack angles and strong tangential blowing, it was observed that the cross section of the wing can hardly be said to be well adapted to the flow picture. According to some pictures on page 2, the flow does not follow the surface of the front flap. A bubble is formed over and in front of the front flap. This bubble is of a nature similar to the bubble which naturally occurs for a wing profile with a jet flap (ref. 3, 5).

From the pictures on page 2 it is also clear that the flow line on the bottom side of the wing goes almost at right angles towards the flap at high angles of incidence. In one case a little test was carried out by varying the downward deflection angle of the rear flap between approximately 15^{o} and approximately 150^{o} at the same time as the front flap was hinged up approximately 40% and vortex flow was established. Observations were then made on how the downward deflection varied. What struck the observers was that the position of the rear flap did not affect the deflection of the air flow very much. This seemed to indicate that it is the rising front flap in connection with tangential blowing in "protection" of the front flap which are the most important factors in obtaining the desired flow picture. (This was also maintained by Hermann Behrbohm more than 2 years ago!)

The wind tunnel model was straight with the same profile all over the span width. "The wing tip" had the same profile and the same dimension as the base of the wing. In spite of this "raw" design of the wing tip it is interesting to observe that it is the three-dimensional aerodynamic phenomena which seem to form the strength of the profile. Do tangential blowing and the flaps form a "vortex whip" which constitutes a soft aerodynamic prolongation and termination of the wing?

Discussion

Data from the wind tunnel tests must be considered as very preliminary. At most they constitute indications of an aerodynamic phenomenon. Data and ideas may contain many undiscovered errors which bring down the whole reasoning in this PM. There is space for many contributions for verifying and quantifying the hypotheses which are proposed. /19

If we for the time being assume that the indications and the hypotheses reflect a physical reality, what is then the potential in "the flow picture of the vortex lift"?

Supplying energy in a tangential direction seems to lead to a "blowing out" of the end tip vortices, at the same time as the rotation over the vortex core is reinforced. This seems to make possible high lifting forces as well as an artificial span width extension which makes the flow above the wing more two-dimensional by referring the induced drag to the distance between the end tip vortices rather than to the span of the wing.

In order to be able to evaluate the quantitative value of this flow picture, it is necessary to have an evaluation of the relationship between the three related quantities lifting force, drag and jet impulse. The potential can be evaluated more easily if the three values C_L, C_D and C_μ are multiplied by the dynamic pressure q times the reference surface S for a specific aircraft.

In the following sample calculation a straight horizontal low speed flight has been selected for an aircraft with vortex lift wing and with the following data similar to aircraft 105:

Weight:	W_g = 50 kN (≅ 5 ton)
Wing surface:	S = 16.3 m^2
Side ratio:	Λ = 4 (aircraft 105: Λ = 5.53)

An equilibrium speed can be calculated with C_L, C_D and C_μ data from the wind tunnel tests according to the diagram on page 4. In a diagram the total drag D and the jet impulse T_μ can be drawn as a function of the flight speed. The sum of D and T_μ indicate the total impulse which is required from the aircraft gas generator for horizontal flight without acceleration. In the diagram below T_μ and $D + T_\mu$ are presented as functions of the speed for two levels of C_μ = 0.4 and C_μ = 0.8.

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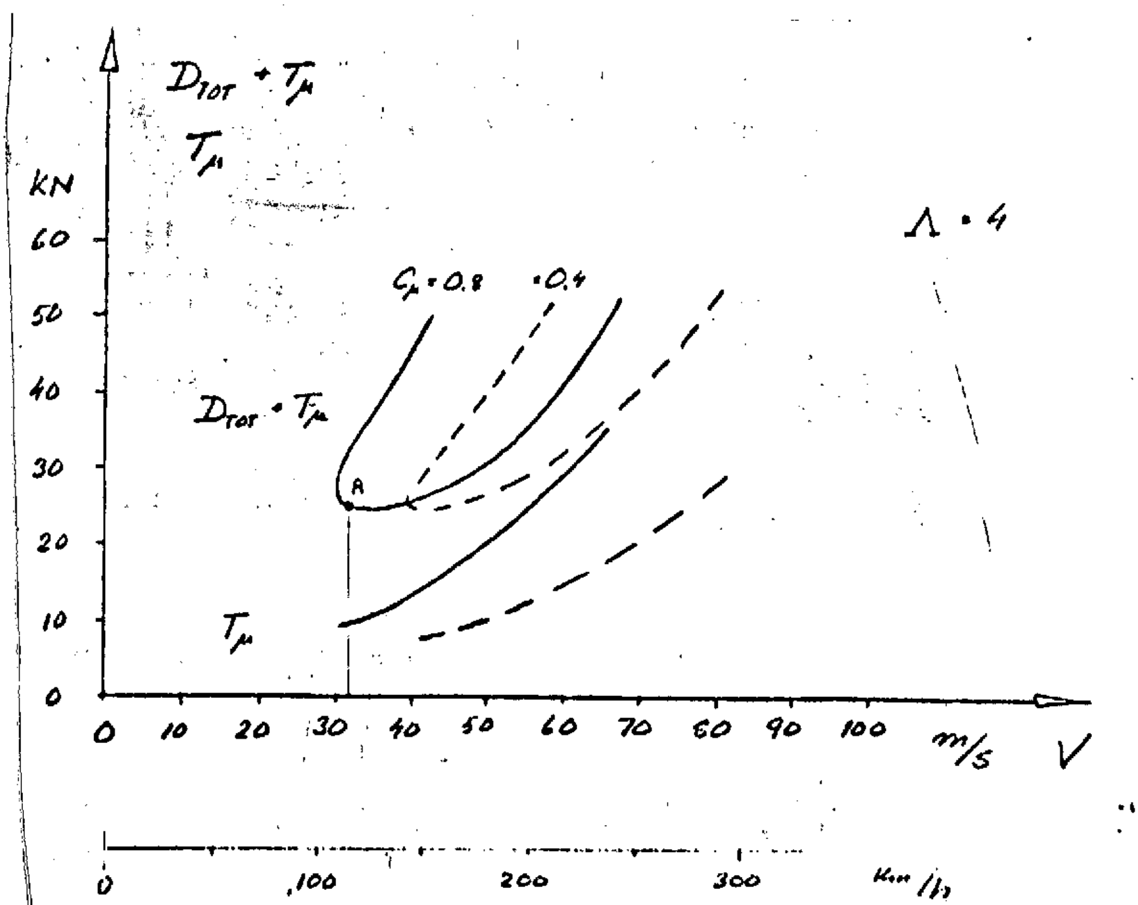


The point A on the diagram corresponds to the set of data:

$C_L = 5$ $\quad W_g = L = 50$ kN (5 tons)
$C_D = 1.6$ $\quad D = 16$ kN (1.6 tons)
$C_\mu = 0.8$ $\quad T_\mu = 8$ kN (0.8 tons)
$V = 31.4$ m/s = 113 km/h

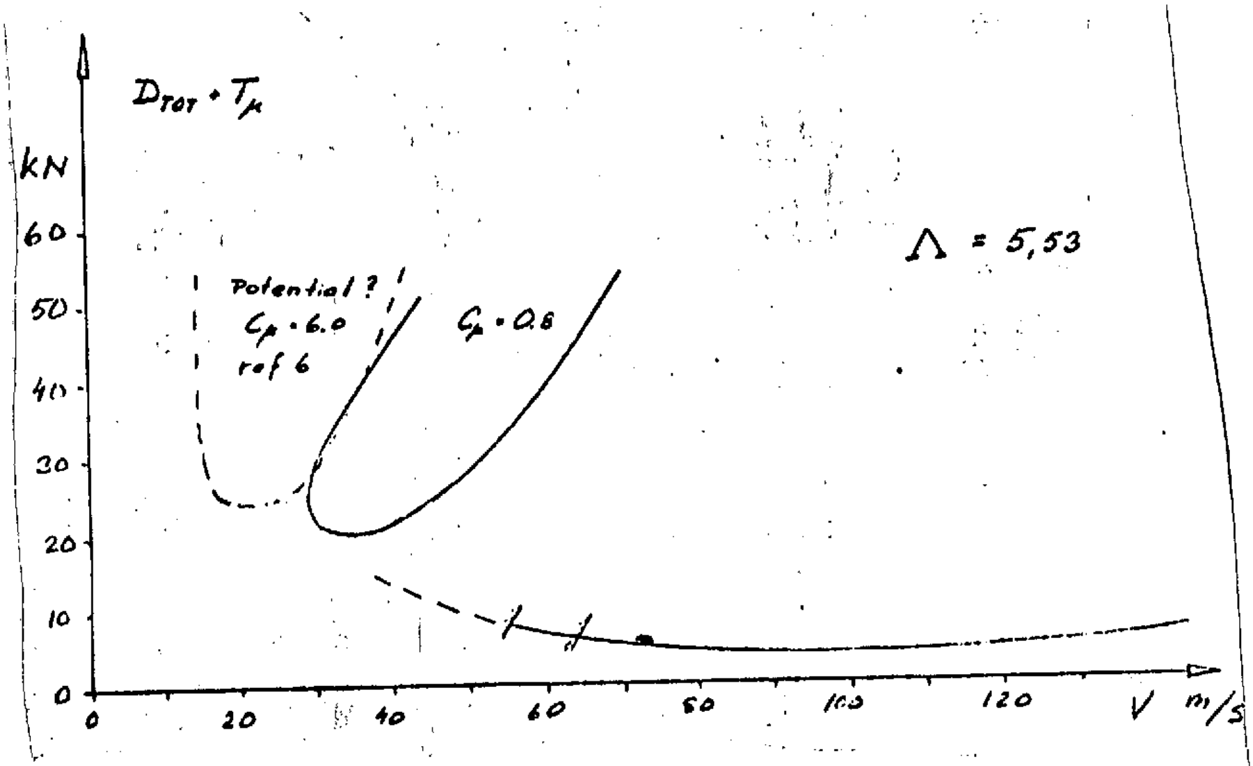
In order to be able to fly horizontally at this equilibrium speed it is necessary to have a gas generator which gives a total impulse of $T_G = D + T_\mu = 16 + 8$ kN = 22 kN (2.4 tons), i.e., the drag in the 105 GE engine combined with a vortex lift wing should make it possible to obtain a takeoff speed of 31.4 m/sec. Purely hypothetical.

The interesting thing which can be read off from the diagram /11 is, however, that a high tangential blow coefficient does not have to involve unreasonable drag force resources (approximately 50% of the weight of the aircraft). In addition it should be noted that doubling the blow coefficient moves the flight area towards lower speeds without any considerable change in the total impulse!

If one is aiming at extremely low speed characteristics, this then indicates that it may be "profitable" to deflect a very large part of the gas generator's jet moment in the form of tangential blowing in order to decrease the induced drag.

A curve for the total drag for a five ton aircraft 105 ($\Lambda = 5.53$) has been drawn on the diagram for comparison. Stall limits corresponding to $C_L = 1.3$ start, and $C_L = 1.7$ landing configuration have been drawn in.

As can be seen from the diagram it is completely necessary with transition forms between a vortex lift mode and "normal" flight. A realistic STOL aircraft project must be based on a design which by means of successive folding in of flaps and reduction of tangential blowing can move and widen the flight area towards the high speed range. It must be possible to fold



the vortex slot into a wing geometry (both plane form and profile) suitable for high speed flight.

Potential and adaptation /12

There is a requirement for short takeoff and landing aircraft. The six day war in the Middle East shows that an air force can be knocked out in a few minutes by attacking the airfields. Domestic flights lose passengers to the railroads because the airfields are moved away from the centers of population.

In view of the law which states that the dynamic pressure grows with the square of the velocity, radical steps are necessary to lower the start and takeoff speed to reasonable values. An approach route speed limit of 70 km/h should be a reasonable goal to strive for as a military and civilian safe start and landing speed. A freeway speed of 110 km/h must be considered to be a temporary goal. These data are selected as examples of the requirement that the aircraft must be adapted to the society of the future.

When formula (2) on page 5 is studied:

$$C_L = 1/2\ \pi \cdot \Lambda \cdot e \cdot \sin\varepsilon$$

it indicates a maximum for deflection angles $\varepsilon = 90^\circ$ and $\sin \varepsilon = 1$.

$$C_{L\ max} = 1/2 \cdot \pi \cdot \Lambda \cdot e \cdot 1$$

With $\Lambda = 8$ and $e = 2$ we obtain $C_{L\ max} \simeq 25$.

Data from wind tunnel tests with a blown cylinder with end disk and strong tangential blowing on the upper side shows that it is possible to reach such levels with very large blow coefficients ($C_L = 20$ and $C_D = 3$ at $C_\mu = 6$ and $\Lambda = 8$, see ref. 6).

Modern combat planes of the type AFTI, and certain aircraft 80 initial designs are designed with both weight and drag resources on the order of magnitude of 5 tons and the two engines placed at the base of the wing next to the outer wings with small side ratios.

This type of combat airplane would probably require high lift properties of the type "vortex lift".

The use of "vortex lift" for civilian use probably lies sometime in the future. The military evaluation of the technique would probably be necessary before it could be utilized commercially.

Questions

An analysis of data in this field from some preliminary /13
wind tunnel tests gives rise to many new questions. These should be considered as suggestions for interesting theses of various types in the field of Clareus and Westesson's contributions.

1. Which C_L, C_D and C_μ configurations can be obtained for extremely high values of tangential blow in the range $C_\mu = 1 - 10$?

2. Can vortex lift function even with wings with large side ratios $\Lambda = 6, 8, 10$?

3. How can the geometry of a vortex lift wing best be designed? Can the protruding part of the rear flap be abolished? Is it possible to achieve high lift values by means of tangential blowing and flap deflections without large angles of attack or changes in the angle of attack (direct lift control)? How?

4. How does the design of the wing tip affect the flow picture? Visualize around and beyond the wing tip. Can "vortex lift" operate with wings with smaller chords towards the wing tip? Constructive suggestions for the flap end and the wing tip design are needed.

5. Can "vortex lift" be generated over swept-back wings? Does the tangential blowing then contribute directly to the drag $= T_\mu \cdot \sin \phi$ in addition to decreasing the induced drag?

6. Which pitch, yaw and roll moments are obtained with a wing with vortex lift? How do these moments vary with C_L, C_D and C_μ? How do the moments vary with various flap deflections?

7. Can control surfaces be used in the area near the wing tip for the control of pitch, yaw and roll moments? How must these control surfaces be designed? How large moments do they give?

8. How is the flow picture of a conventional emphennage in the form of fin and stabilizer placed behind a wing with "vortex lift" affected?

9. How is the vortex flow affected by an admixture of hot air /14
flow from the gas generator? Can the excess heat energy affect the thermodynamicsand the flow mechanics of the vortex

flow? How will the energy from the gas generator be supplied to the vortex slot? Does blowing of a concentrated jet in a radial direction constitute the best way of feeding energy into a vortex flow? Can blowing in the vortex core be complemented or replaced by a feeding in of energy at the periphery of the vortex?

10. Which flow parameters are relevant in order to be able to evaluate the stability of a vortex flow? To what extent does a wing utilizing vortex lift depend on the Reynolds number? On which dimensions and on which velocity and on which temperature should a calculation of these flow parameters (e.g., Re) be based in order for the models to be meaningful?

11. What installation problems occur if one wants to deflect approximately 50% of the gas generator's impulse to the generation of vortices? Where the must the engines be placed on a four engine commercial aircraft utilizing vortex lift? Five suggestions are needed.

12. If the induced drag can be affected and controlled in the way indicated here, how can we set up an overall mathematical model for the vortex lift flow picture?

Fig 1.1
FFA's smoke tunnel
V = 2.5 m/sec
Model 1,
$\alpha = 10^{\circ}$

Fig. 1.2
$\alpha = 15^{\circ}$

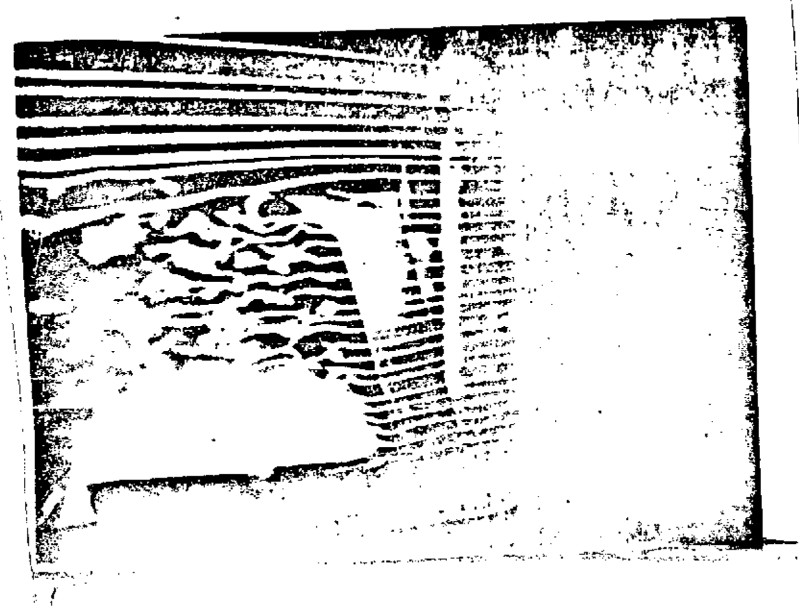


Fig. 1.3
$\alpha = 18^{\circ}$

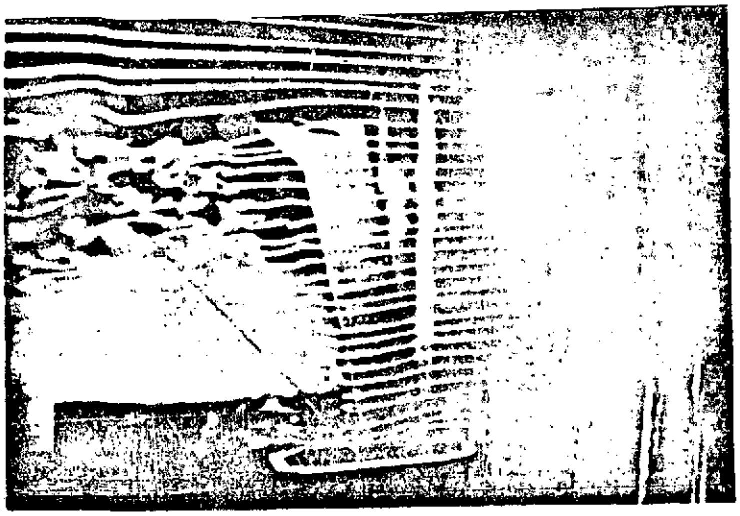


Fig. 1.4
model 1,
$\alpha = 21^{o}$

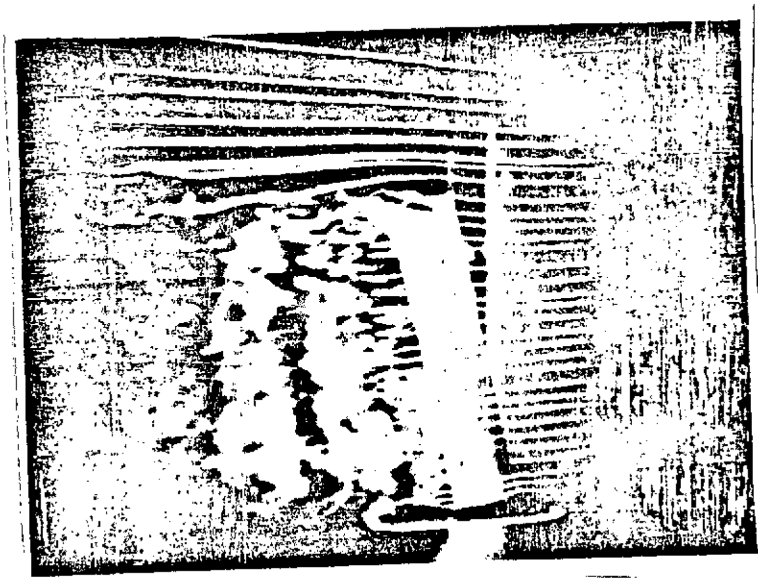


Fig. 1.5
$\alpha = 24^{o}$

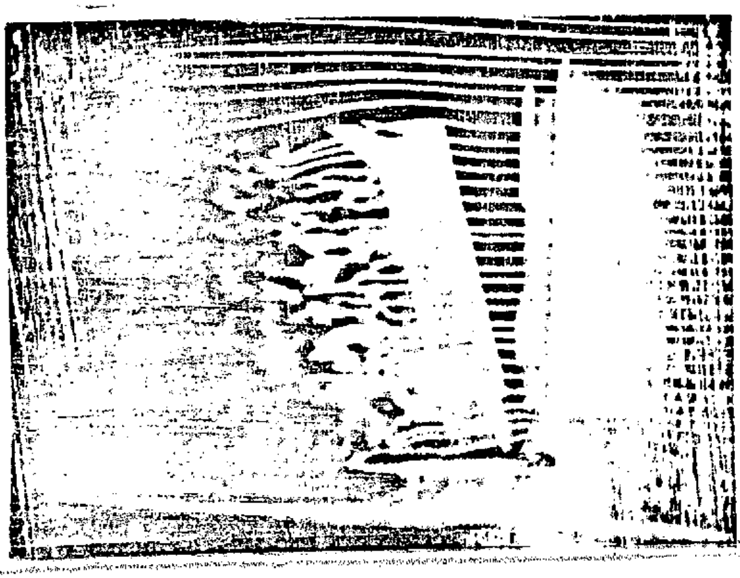


Fig. 1.6
$\alpha = 27^{o}$

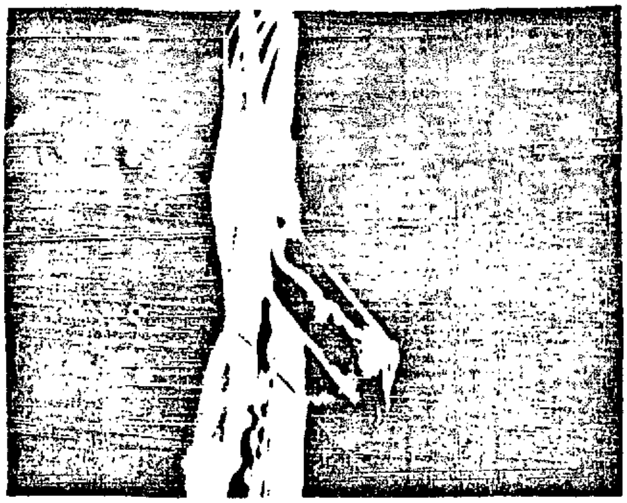


Fig. 2.1
FFA's smoke tunnel; model 2.
V = 2.5 m/sec
$\alpha = 14^{\circ}$, $\phi = 60^{\circ}$
Vortex not stable

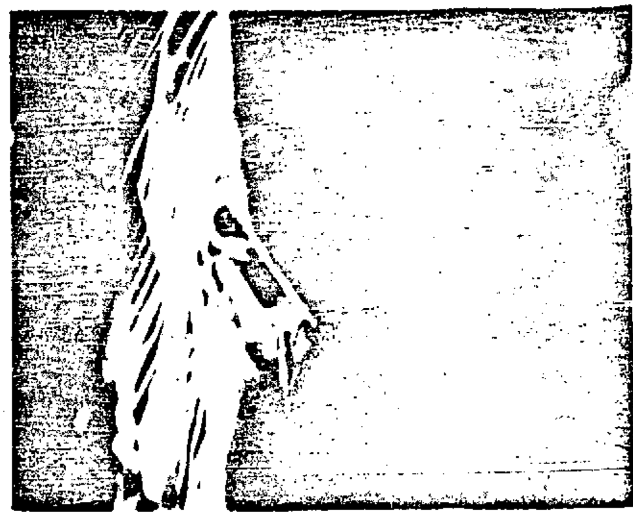


Fig. 2.2
Model 2, $\alpha = 18^{\circ}$, $\phi = 60^{\circ}$
Vortex not stable.

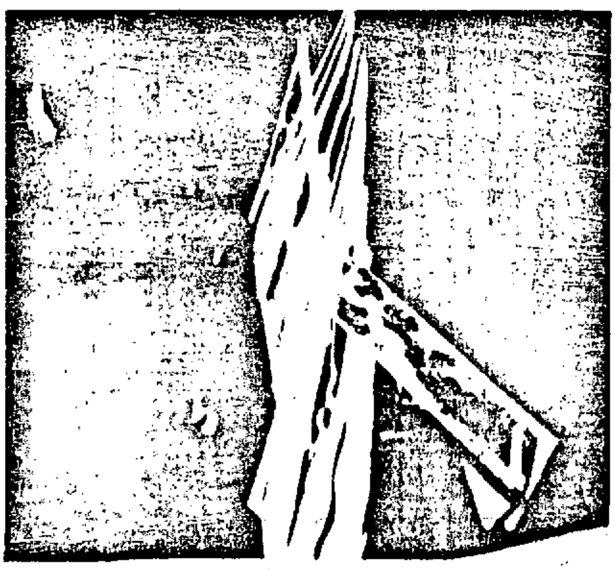


Fig. 3.1
Model 3, $\alpha = 12^{\circ}$, $\phi = 52^{\circ}$
Vortex not stable.

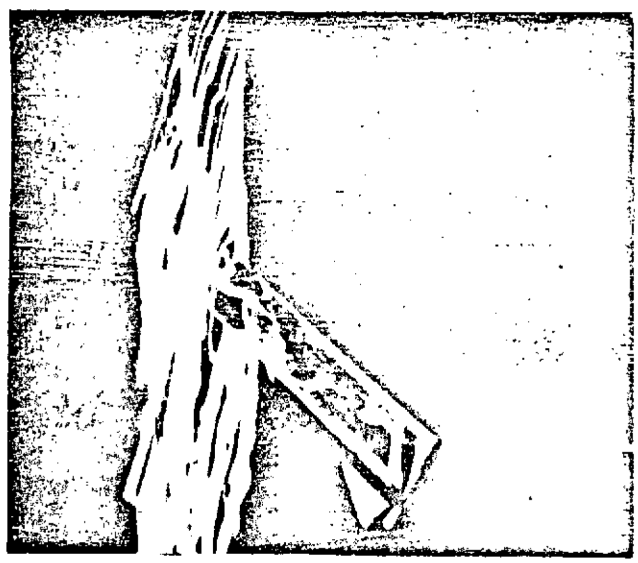
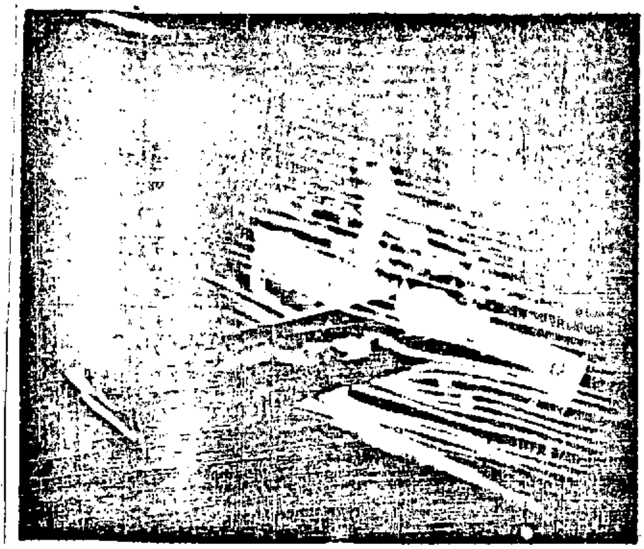


Fig. 3.2
Model 3, $\alpha = 12^{\circ}$, $\phi = 52^{\circ}$
Vortex not stable.



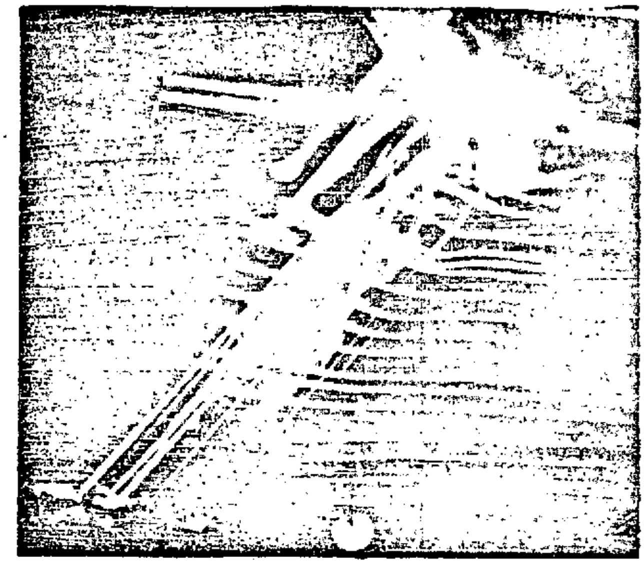
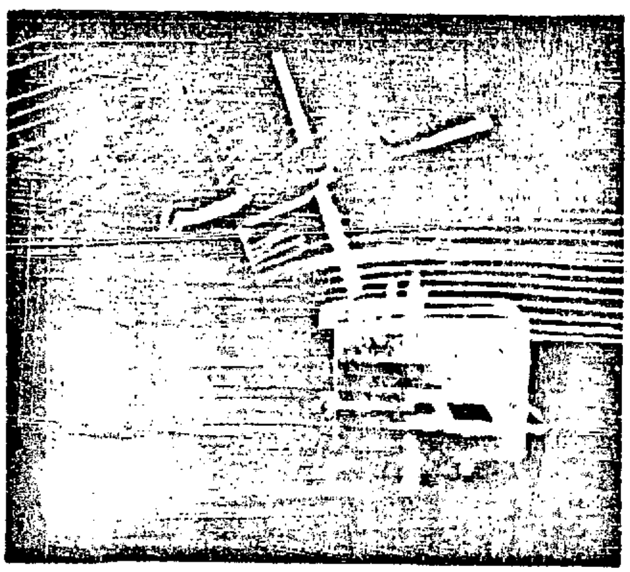


Fig. 4.1
Model 4, α : slightly negative.
ϕ : approx. 30°, vortex not stable

Fig. 4.2. As figure 4.1



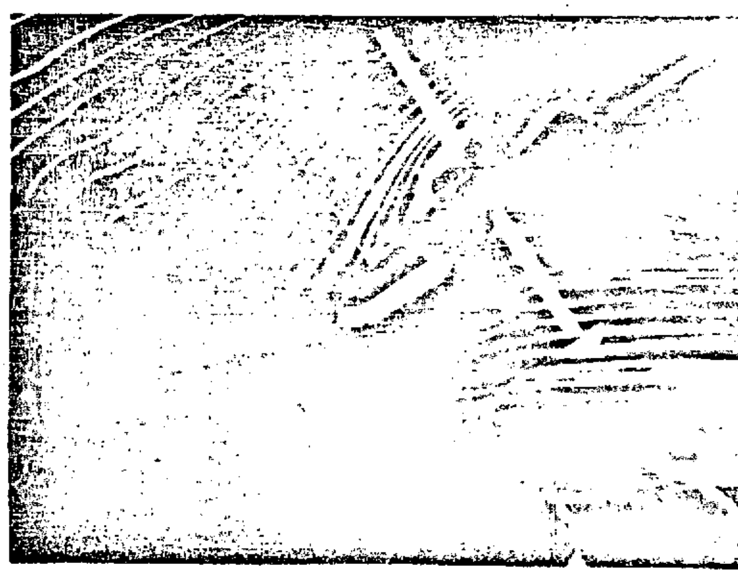


Fig. 5.1
Model 5: Flap blowing with large blow coefficient. α approx. 15°, ϕ = 30°.

Fig. 5.2
As figure 5.1, α approx 40°.

Fig. 7.1
FFA's smoke tunnel, V = 2.5 m/sec
Blowing in chord direction;
$C_{b,c} \neq 0$, sweep-back angle ϕ = 45°, $\alpha = 0^{\circ}$, model 7 (original condition).

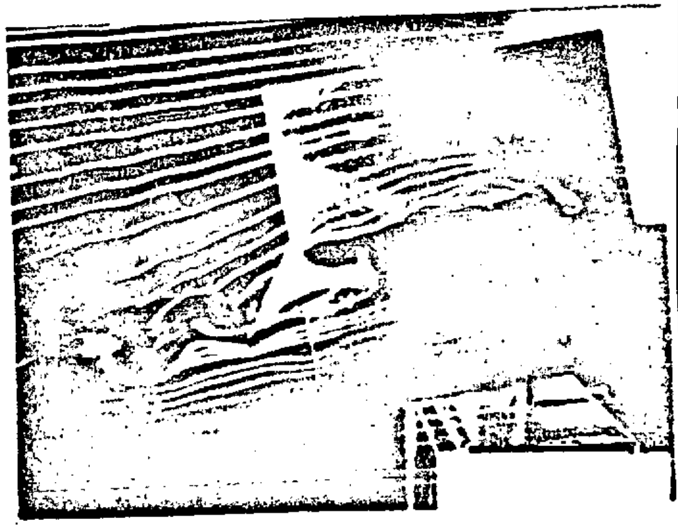


Fig. 7.2
$\alpha = 10^{\circ}$

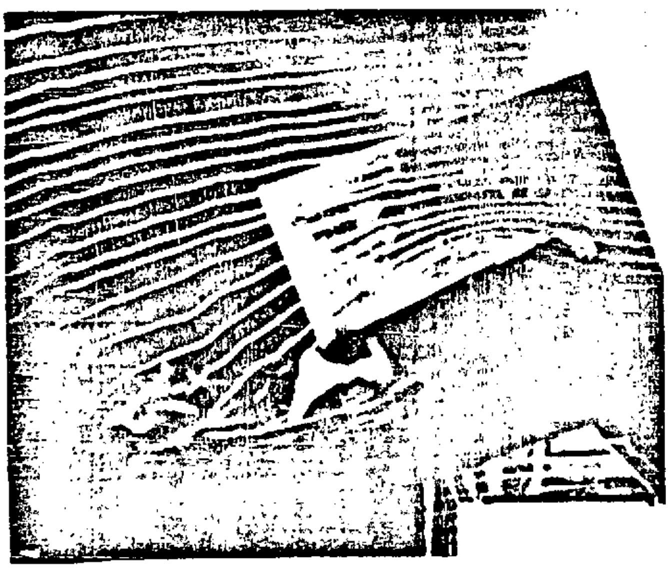


Fig. 7.3
$\alpha = 20^{\circ}$

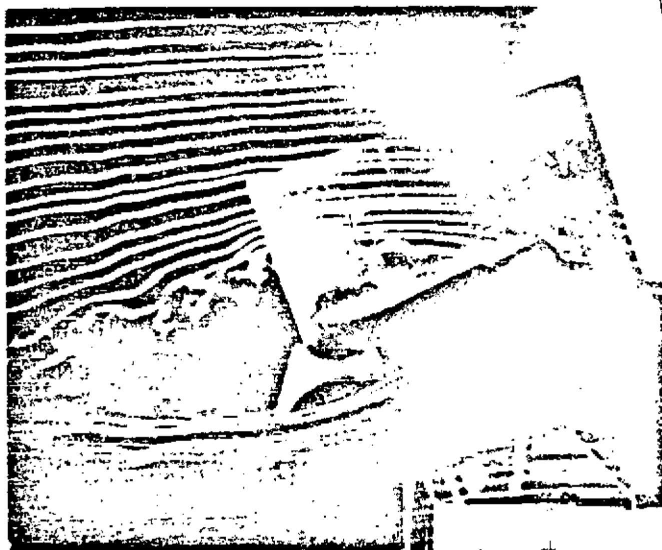


Fig. 7.4
$\alpha = 20^{\circ}$, $C_{b,c} = 0$.

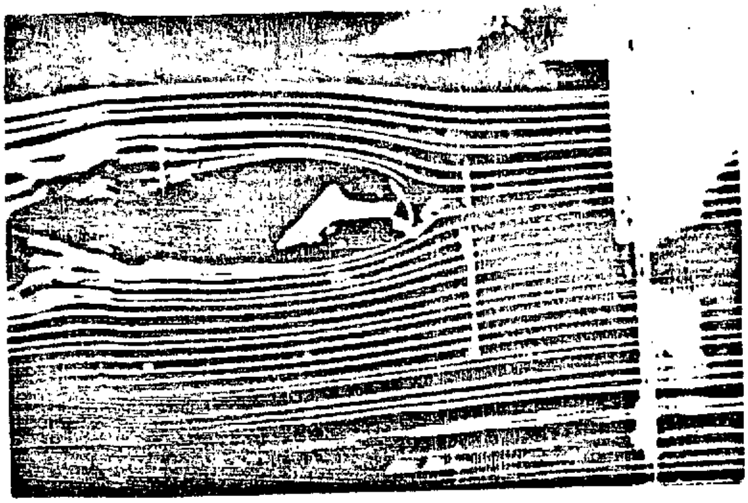


Fig. 7.5
FFA's smoke tunnel.
V = 2.5 m/sec
The blow coefficient
$C_b = 0$, sweep-back
angle $\phi = 0^o$, span
section $y = 0.7\ b/2$,
$\alpha = 0^o$,
Model 7.
Blowing approximately
at chord = 35%.

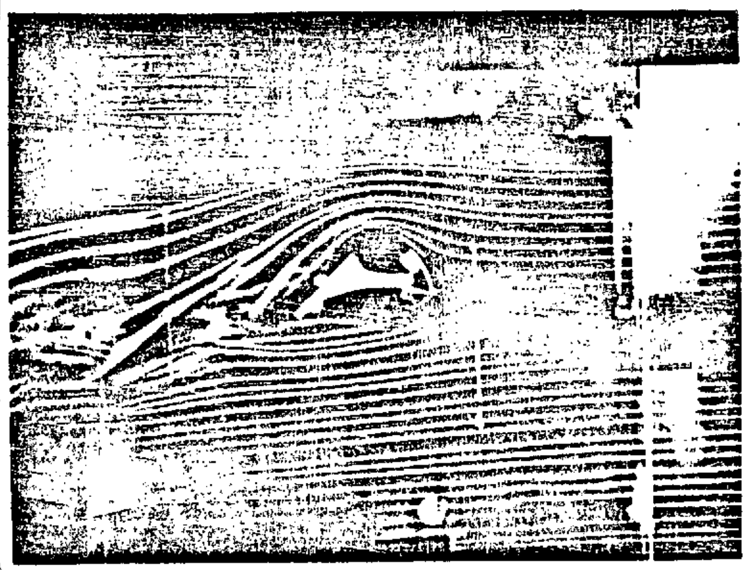


Fig. 7.6
$C_b \neq 0$,
$\alpha = 0^o$.

Fig. 7.7
$\alpha = 10^o$.

Fig. 7.8
Model 7,
$\alpha = 20^{\circ}$,
$C_b \neq 0$,
$y = 0.7\ b/2$
$\phi = 0^{\circ}$.

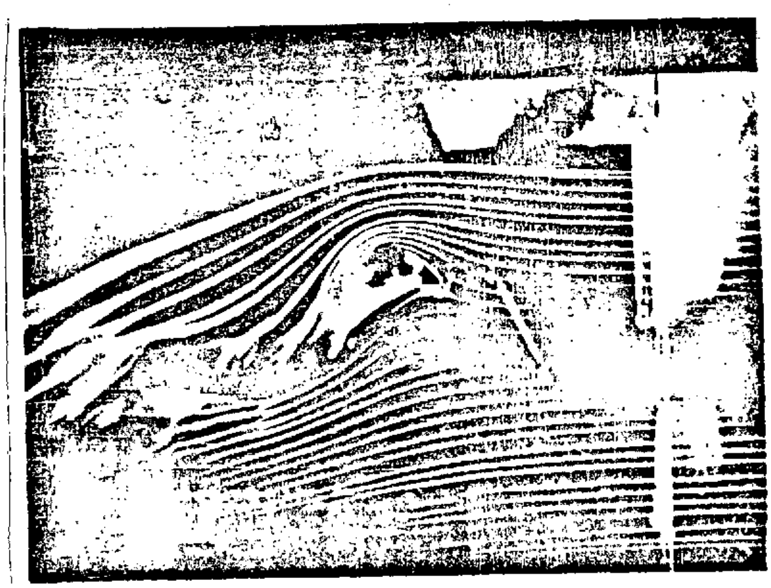


Fig. 7.9
$\alpha = 30^{\circ}$

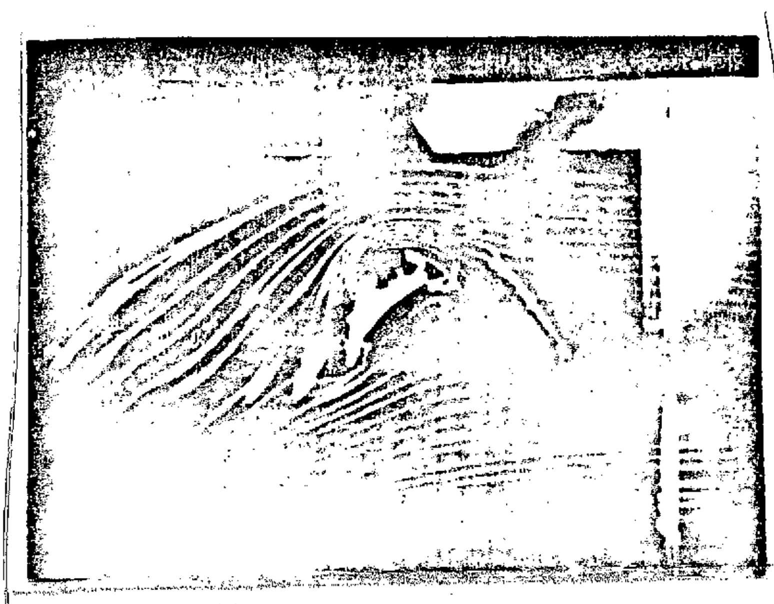


Fig. 7.10
$\alpha = 40^{\circ}$

Fig. 7.11
Model 7,
$\alpha = 50^{\circ}$,
$C_b \neq 0$,
$y = 0.7\ b/2$,
$\phi = 0^{\circ}$.

Fig. 7.12
$\alpha = 60^{\circ}$

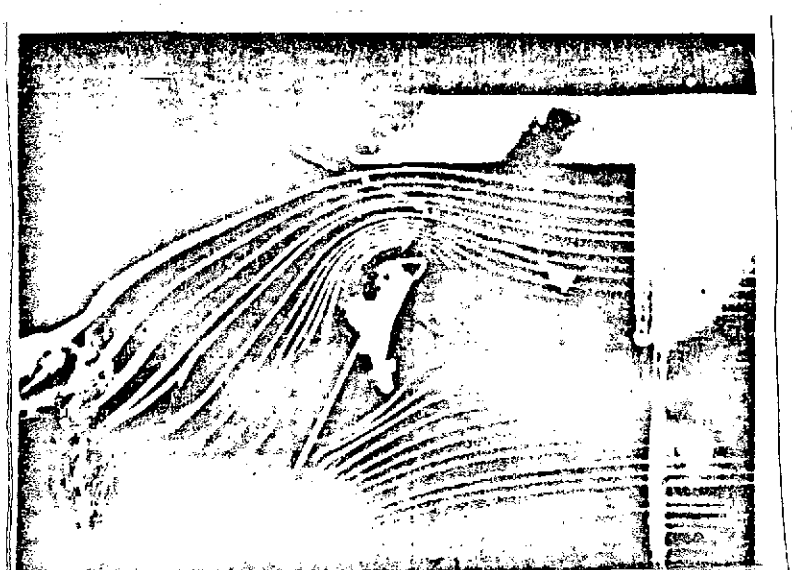


Fig. 7.13
$\alpha = 70^{\circ}$

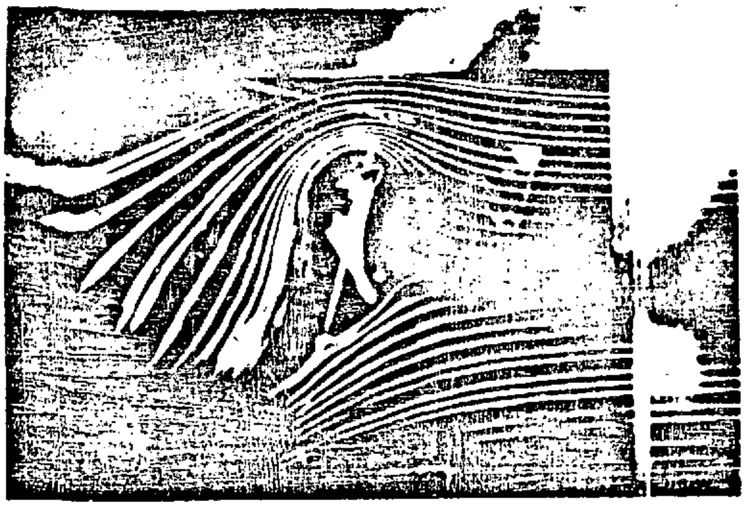


Fig. 7.14
Model 7,
$\alpha \neq 80^{\circ}$
$C_b \neq 0$,
$y = 0.7\ b/2$,
$\phi = 0^{\circ}$.

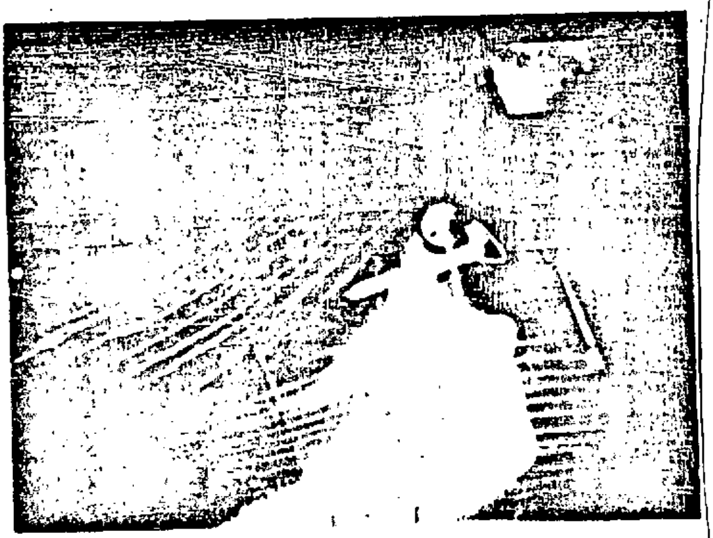


Fig. 7.15
Model 7. $C_b \neq 0$,
"Vane" at $y = 0.7\ b/2$.
α approx 20°.

Fig. 7.16
FFA's smoke tunnel.
V = 2.5 m/sec.
Model 7,
blow coefficient
$C_b \neq 0$, sweep-back
angle $\phi = 30^\circ$,
the smoke loops at
span section $y = 0.55\ b/2$,
$\alpha = 0^\circ$.

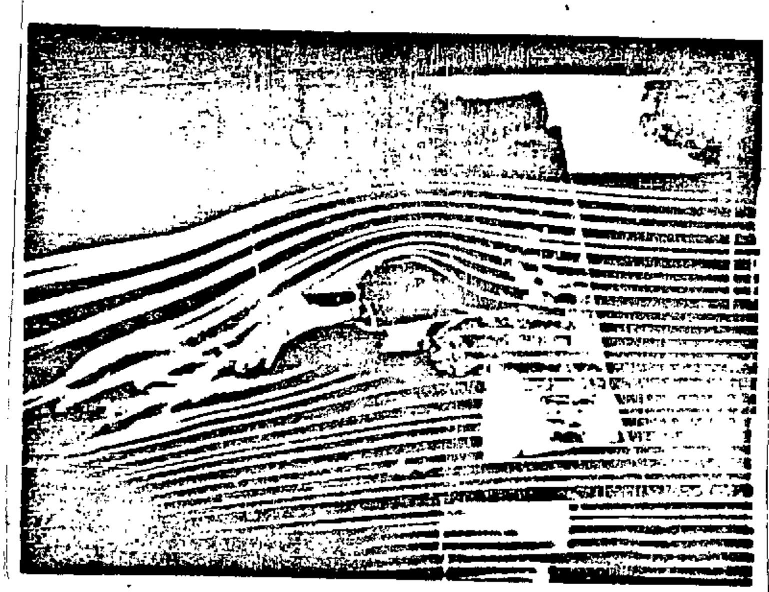


Fig. 7.17
$\alpha = 10^\circ$.

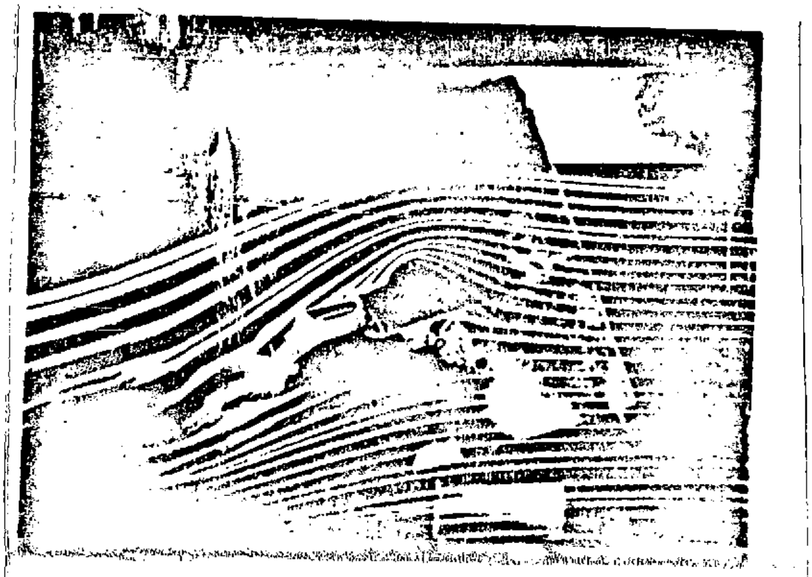


Fig. 7.18
$\alpha = 20^\circ$

Fig. 7.19
Model 7
$\alpha = 30^{\circ}$,
$C_b \neq 0$,
$y = 0.55\ b/2$,
$\phi = 30^{\circ}$.

Fig. 7.20
$\alpha = 40^{\circ}$.

Fig. 7.21
$\alpha = 50^{\circ}$.

Fig. 7.22
Model 7
$\alpha = 60^\circ$,
$C_b \neq 0$,
$y = 0.55\ b/2$,
$\phi = 30^\circ$.

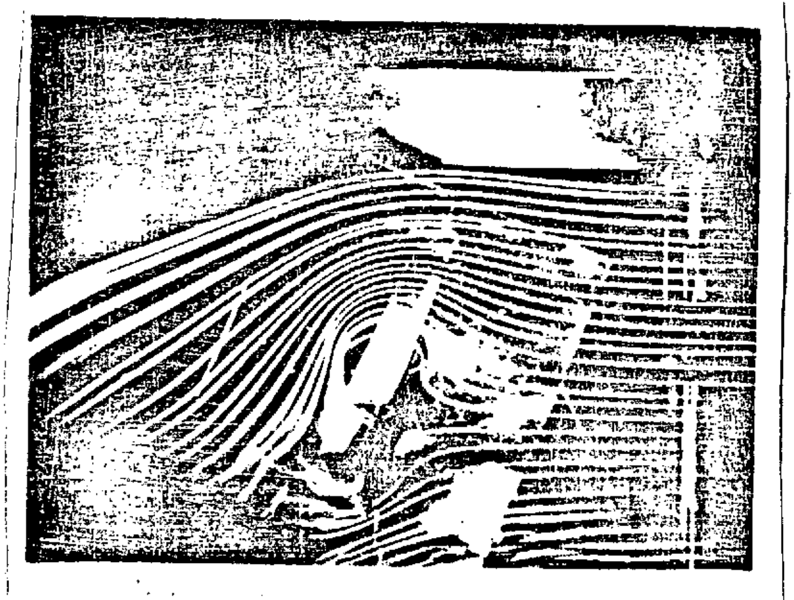


Fig. 7.23
$\alpha = 70^\circ$.

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